Experimental Doppler Radar

or how to build your own speed trap

Features

- Measures speed of moving targets
- Commercially available low power radar module
- K-band (24 GHz)
- Range 60 m minimum; 100 m usable
- Resolution 0.24 m/s
- Easy-to-understand digital signal processing
- Universal dsPIC baseboard can be repurposed for other applications

PROJECT INFORMATION

Doppler
radar
DSP FFT

entry level
intermediate level
➡ expert level

4 hours approx.

SMD soldering tools,
dsPIC programmer,
MPLAB-X

€150 / £145 / $155 approx.

By Kai Hiltunen (Finland)

A couple of years ago I read an article about small radars [2]. After that I also began noticing product news items from various companies about small, low-cost radar transceiver chips and modules, and so I decided to do a hobby project on microwave radar. Here's what I came up with.

The aim of the project was to build a microwave Doppler radar by using a, low-cost off the shelf radar module.

The most interesting thing as I see it was to learn new things and make electronics bits and pieces work as planned.

Of course, it's also important to assign some practical use to the final product. For example, a Doppler radar may measure the speed of a ball, a bicycle or a running person, which may turn out to be pretty entertaining among the more sporty kids in the neighbourhood.

A little bit of Doppler radar theory

A radar transmits a signal using its transmit antenna. When the signal hits upon an obstacle a portion of the transmitted energy gets reflected and is received, heavily attenuated of course, by the

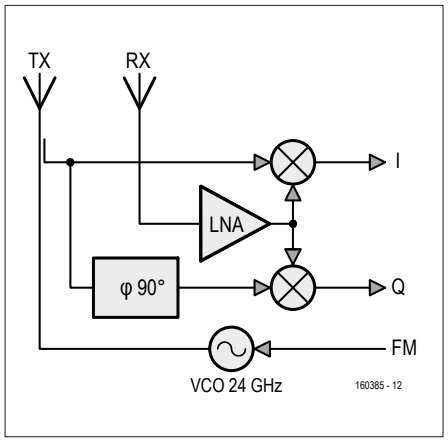


Figure 1. All this circuitry is housed inside the 25.4 × 25.4 × 6 mm (1″ × 1″ × 0.25″) K-LC5 Doppler radar transceiver module.

radar's receive antenna. If the transmitted signal was modulated in some way, for instance AM or FM, the radar can calculate the distance to the obstacle based on the measured "time of flight" of the return signal. If the signal is unmodulated and continuous, as in this project, it's not possible to measure the distance. However, movements of the obstacle can still be detected thanks to the Doppler effect or shift of the reflected signal. The Doppler effect produces a change in frequency of the signal due to movement. If the transmitted signal meets an obstacle — a target in radar terminology —, which moves directly towards the radar, the frequency shift Δf of the reflected signal compared to the transmitted frequency is equal to

$$\Delta f = 2v \times f_0 / c \quad [\text{Hz}]$$

or

$$v = \Delta f \times c / 2f_0 \quad [\text{m/s}]$$

In this formula v is the speed of the target, f_0 is the transmitter frequency and c is the speed of light. To give you an idea: when f_0 equals 24 GHz an object speed v of 1 m/s produces 160 Hz worth of Doppler shift.

The block diagram of the radar module I selected for my experiments is shown in **Figure 1**. The transmitted signal is generated by a voltage controlled oscillator (VCO) operating in the frequency range of 24.050 to 24.250 GHz. The tuning voltage input FM of the module can be used to modulate the VCO's frequency. In this application, however, a simple continuous wave Doppler radar is built and the tuning input is not needed.

The oscillator output is connected to the transmit antenna via a directional coupler. Thanks to the directional coupler most of the signal energy flows to the transmit antenna, but some of it is also coupled to the receive path RF mixers, allowing the transducer to sample the transmitted signal and use it as a reference signal in the receive path.

The RF mixer is a three-port component with a Radio Frequency (RF), Intermediate Frequency (IF) and Local Oscillator (LO) port. An RF mixer can be understood as a non-linear component which produces at its IF output port the sum and difference frequencies of the LO and RF signals.

Let's look at an example

Suppose that the transmitted (TX) signal frequency is 24.1 GHz and this signal inevitably also leaks to the receiver mixer for an LO signal (note the almost connected line in Figure 1). Imagine that the signal reflected by some object — our target — received by the receive antenna and fed to the mixer's RF port (RX), is at 24.100001 GHz, i.e. 1 kHz up from the TX frequency. Because the mixer produces at its IF output the sum and difference frequencies of LO and RF, there will be a sinusoidal signal with a frequency of 1 kHz (the difference) together with a signal with a frequency of 48.200001 GHz (the sum). Of course, there will also be some interference, noise and other harmonic components, but they are either supressed or otherwise not significant.

If we plug the value of 1 kHz into the equation presented above, together with f_0 = 24.1 GHz and c = 3 × 10^8 m/s we find an object speed of 6.2 m/s or 22.4 km/h.

Note that if the RX signal was 1 kHz under LO, then there would be the same 1 kHz IF output signal. The frequencies 24.100001 GHz and 24.099999 GHz are so-called image frequencies because they produce the same signal at the IF output.

The radar module depicted in **Figure 1** has two mixers with two outputs labelled 'I' and 'Q'. These are the so-called in-phase ('I') and quadrature ('Q') signal components. The 'I' and 'Q' signal paths are identical except for a 90° phase shifter in the 'Q' branch. From the phase relationship between 'I' and 'Q' it is possible to determine whether RX was above or below LO.

In the project presented here the image frequency issue is ignored and only the 'I' output of the mixer is used. As a consequence we can only determine the so-called radial speed of the target, i.e. we cannot say whether the target is moving towards the radar or away from it as RX may be either at 24.1000001 GHz or 24.099999 GHz.

Circuit operation

Based on the presentation above the job of the required circuit and the signal processing software becomes evident: accurately measure the frequency of a sinusoidal signal at the mixer's IF output port, convert it to a speed value and present it to the user. So how do we go about?

The circuit schematic is presented in **Figure 2**. The radar module chosen as the core of this project is the RFBeam Type K-LC5, a low-cost K-band radar transceiver. This module handles all the complicated high-frequency and microwave radar operations, allowing the rest of the circuit to deal with low-frequency electronics and signal processing. Note that there's also a v2 version of this module which does not have a VCO and consequently no FM input.

First limit the input signal bandwidth

The transceiver's 'I' output is fed into an active bandpass filter IC10.B designed and simulated with the free LTspice circuit simulator. The –3dB bandwidth of the filter covers the frequency range from 70 Hz to roughly 7 kHz. Using the Doppler shift equation presented above the maximum speed we can measure is therefore about 45 m/s, i.e. about 160 km/h. This is adequate if the radar is used to measure the speed of a ball or a bicycle, for example. The voltage gain of the circuit is 20 in order to amplify the signal to a suitable level for the A/D converter. The transfer function of the simulated circuit is presented in **Figure 3**.

Sample it

The filtered and amplified IF signal exiting from the transceiver is sampled by IC2, an AD7680 A/D converter (ADC). This converter is a 16-bit successive approximation converter capable of a maximum sampling rate of 100 kHz (kSPS or kilosamples per second). ADC conversions are initiated by the controller IC1 based on a timer running at a fre-

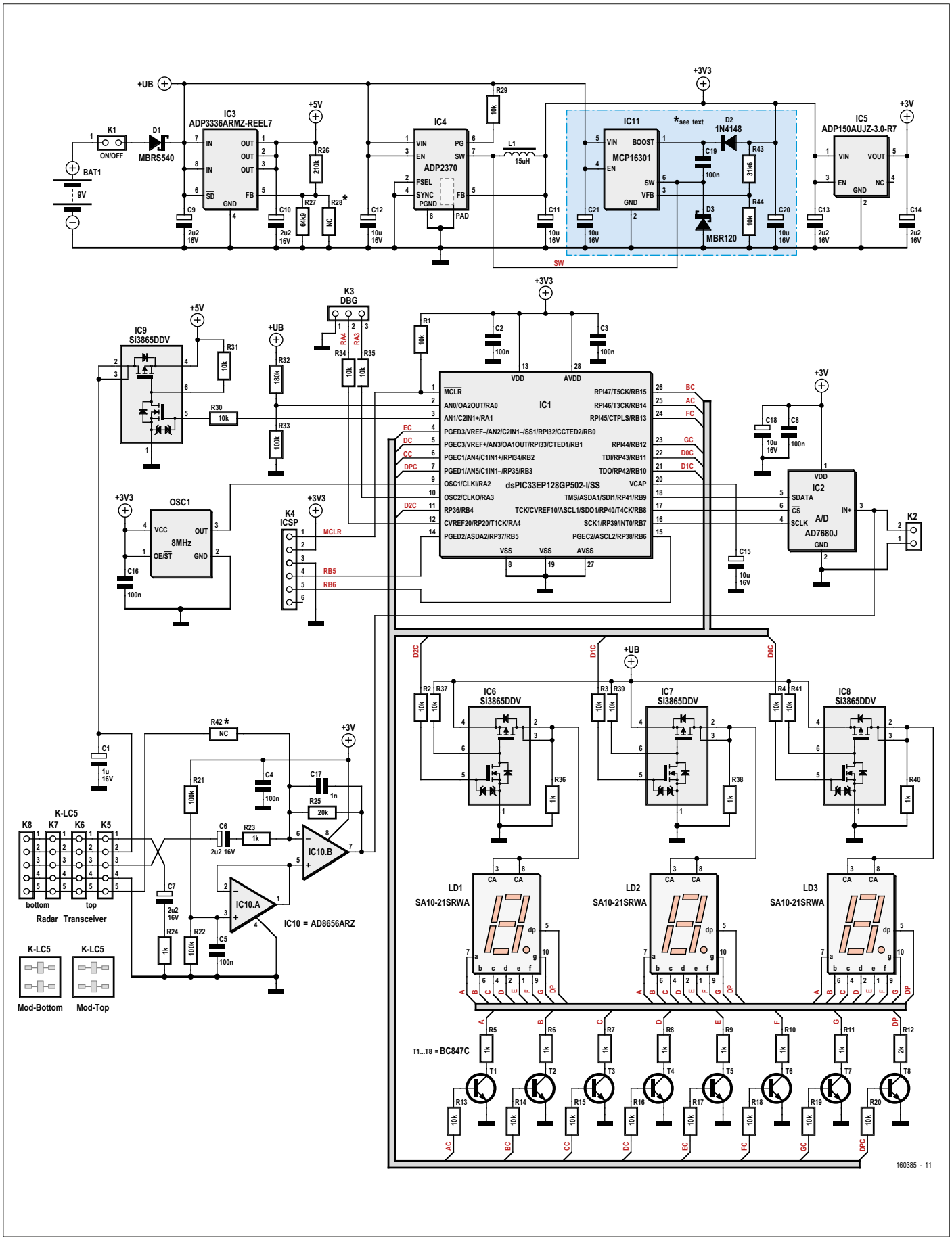


Figure 2. The power supply at the top of the schematic generates three voltages from a 9-volt battery: +5 V, +3.3 V and 3 V. The bottom-right shows the 7-segment display and its LED drivers. The radar transceiver module is connected to one of the sockets K5, K6, K7 or K8, where K5 and K6 are mounted at the top side of the board while K7 and K8 are mounted at the bottom side.

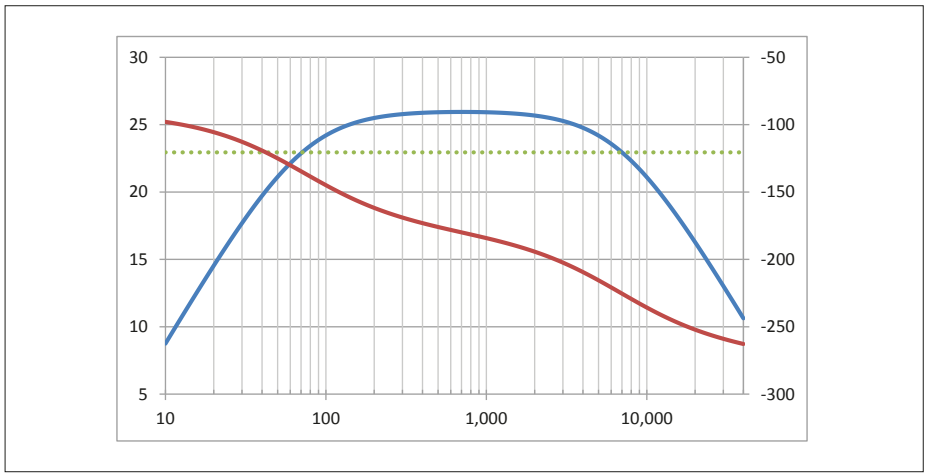


Figure 3. LTspice simulation of the bandpass filter built around IC10. Magnitude in decibels is in blue, the dashed green horizontal line is at –3dB from the maximum of the blue line, and the phase follows the red line. The horizontal axis represents the frequency in hertz.

quency of 60 kHz. The conversion result is read through an SPI port.

In addition to supervising the sampling process, digital signal controller IC1 also 'actuates' the power switch of the radar module and updates the three multiplexed 7-segment displays. Roughly eight measurements per second are taken. When not sampling, the radar module is switched off with the help of IC9, a handy load switch that combines an N- and P-channel MOSFET in a single package.

The same type of load switch is used to multiplex the three 7-segment displays. The common anode (CA) pin of the active display is switched on while the other two displays are switched off. The cathode pins of the displays are controlled via BJT transistors T1–T8.

Power supply

Although the circuit is intended for powering from a 9-volt battery, input voltages up to 12 V are acceptable. The battery voltage is used directly to drive the 7-segment displays. A linear regulator, IC3, provides the 5-V supply for the radar module. A switching regulator constellation (IC4/IC11) is used to produce a 3.3-volt supply voltage for IC1 and its reference oscillator OSC1. A low-dropout (LDO) regulator (IC5) stabilises this further to obtain a low-noise 3-volt supply for the operational amplifiers and the ADC.

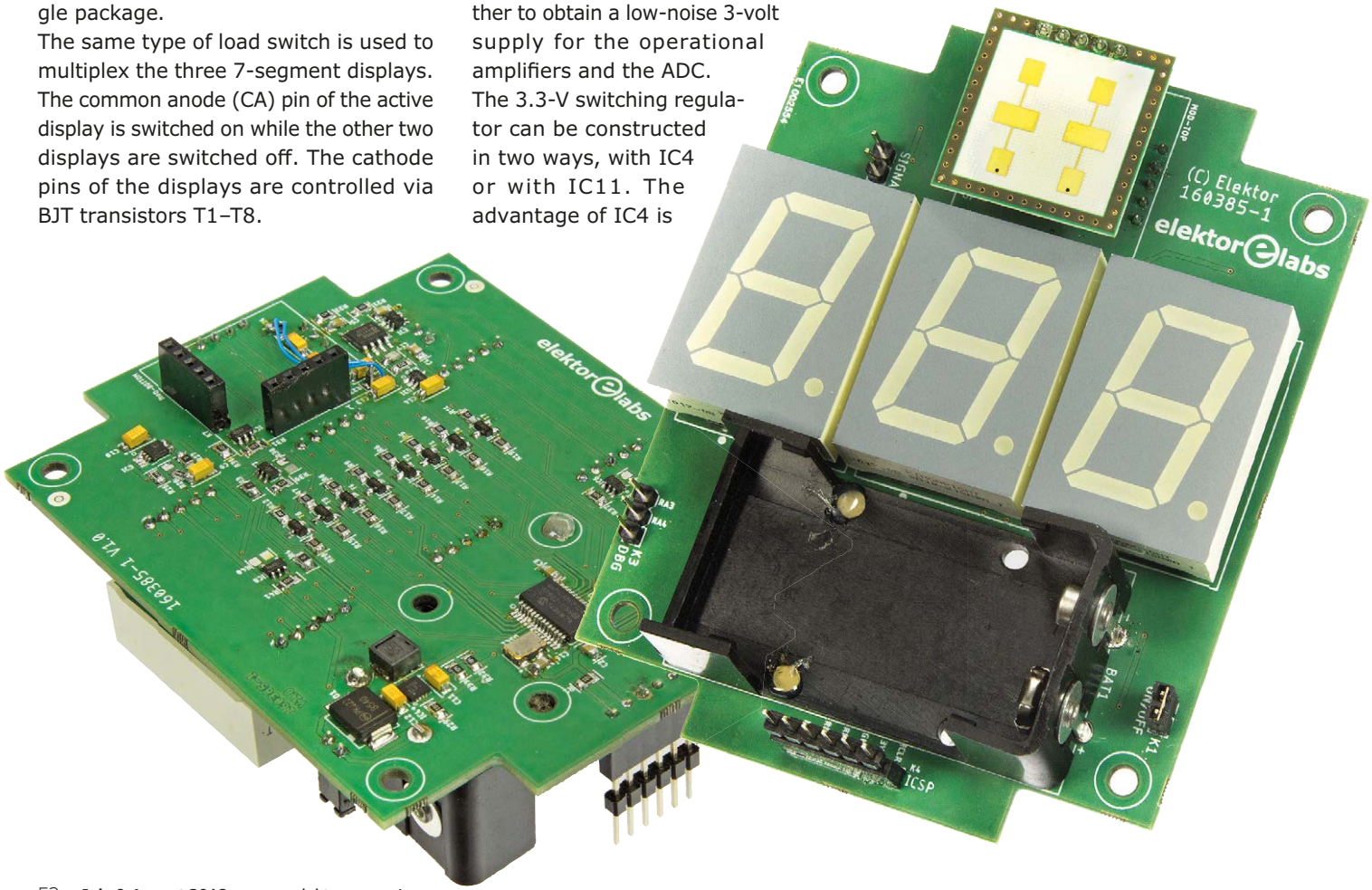
The 3.3-V switching regulator can be constructed in two ways, with IC4 or with IC11. The advantage of IC4 is that fewer components are needed (C19, C20, C21, D2, D3, R43, R44 and IC11 should not be mounted in this case), but it is difficult to solder without a reflow oven. For this reason we added a second option based on IC11 (in this case do not mount IC4 and R29). Due to the extra components there is no real cost difference, but IC11 comes in a more convenient 6-pin SOT-23 package. Parts C11, C12 and L1 are required in both configurations.

Position R28 is provided in case you can't find a resistor with a value of 64.9 kΩ. Good old 68 kΩ in parallel with 1.5 MΩ is a close enough match. R28 also comes in handy if fine-tuning is needed for some reason.

R42 affords an input for testing the signal processing chain. K2 can be used for this too, but effectively skips the bandpass filter. K2 can also be useful for experimenting with the radar transceiver output signal in another set-up or simply for inspecting it on an oscilloscope.

R32 and R33 provide a way for the controller to measure the battery voltage. The current software does not use this option.

Current consumption of the circuit is about 100 mA when the radar module is switched on and around 30 mA oth-



erwise. The observed measurement frequency was 8 Hz. With a duty cycle of 22% this gives an average current consumption of 45 mA.

Software operation

Barring the libraries, the source code for this project fits in one file [1] and is divided into a handful of functions that will be described in this section.
After power-on reset the system is initialised. This includes the initialisation

Handle with care

The K-LC5 Doppler radar transceiver module is sensitive to static electricity so you may want to be careful with it.

COMPONENT LIST

Resistors

R28,R42 = not fitted*
R5-R11,R23,R24,R36,R38,R40 = 1kΩ
R12 = 2kΩ
R1-R4,R13-R20,R29*,R30,R31,R34,R35,R37, R39,R41,R44* = 10kΩ
R25 = 20kΩ
R43* = 31.6kΩ
R27 = 64.9kΩ
R21,R22,R33 = 100kΩ
R32 = 180kΩ
R26 = 210kΩ

Capacitors

C17 = 1nF
C2,C3,C4,C5,C8,C16,C19* = 100nF
C1 = 1µF 16V
C6,C7,C9,C10,C13,C14 = 2.2µF 16V
C11,C12,C15,C18,C20*,C21* = 10µF 16V

Inductor

L1 = 15µH

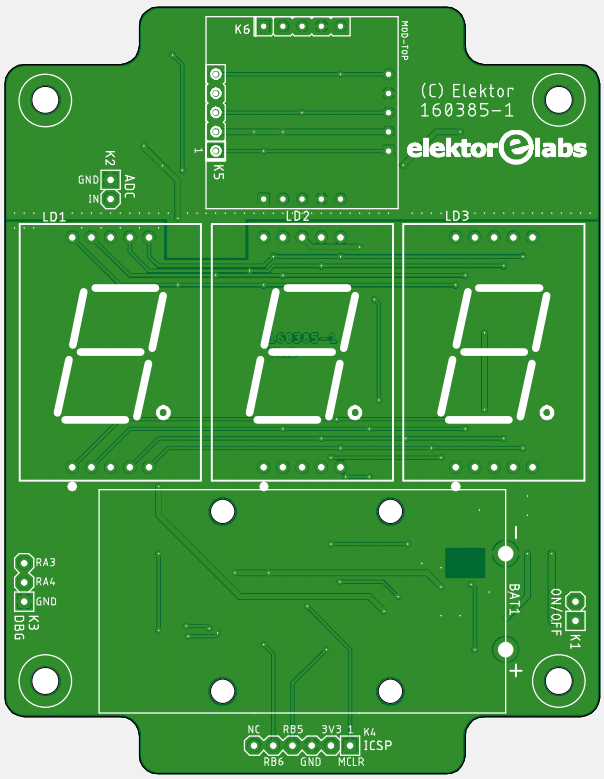
Semiconductors

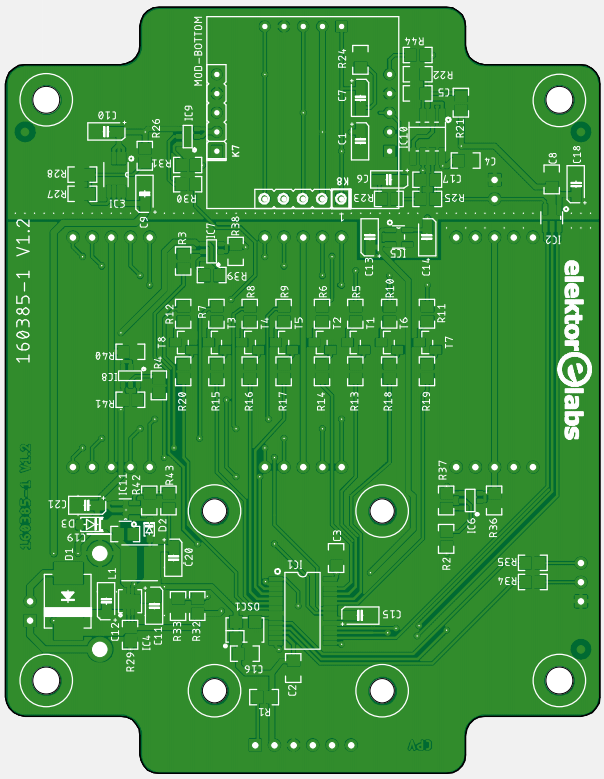
D1 = MBRS540
D2* = 1N4148WS
D3* = MBR120
IC1 = dsPIC33EP128GP502 -I/SS
IC2 = AD7680 -ARJZ
IC3 = ADP3336 -ARMZ
IC4* = ADP2370-3.3
IC5 = ADP150AUJZ-3.0-R7
IC6,IC7,IC8,IC9 = SI3865DDV
IC10 = AD8656ARZ
IC11* = MCP16301
LD1,LD2,LD3 = 7-segment display, CA, 1" height, SA10-21SRWA
OSC1 = 8MHz oscillator module, Abracon ASFL1-8.000MHZ-EK-T
T1,T2,T3,T4,T5,T6,T7,T8 = BC847C

Miscellaneous

BAT1 = 9V battery holder Keystone 1294
K1,K2 = 2-pin pinheader, 0.1" pitch
K3 = 3-pin pinheader, 0.1" pitch
K4 = 6-pin pinheader, 0.1" pitch
K5,K6,K7,K8 = 5-way pinheader socket, 0.1" pitch
RFBeam type K-LC5 Doppler radar transceiver
Power switch or jumper for K1
Enclosure: Bud Industries PN-1323-C
PCB # 160385-1

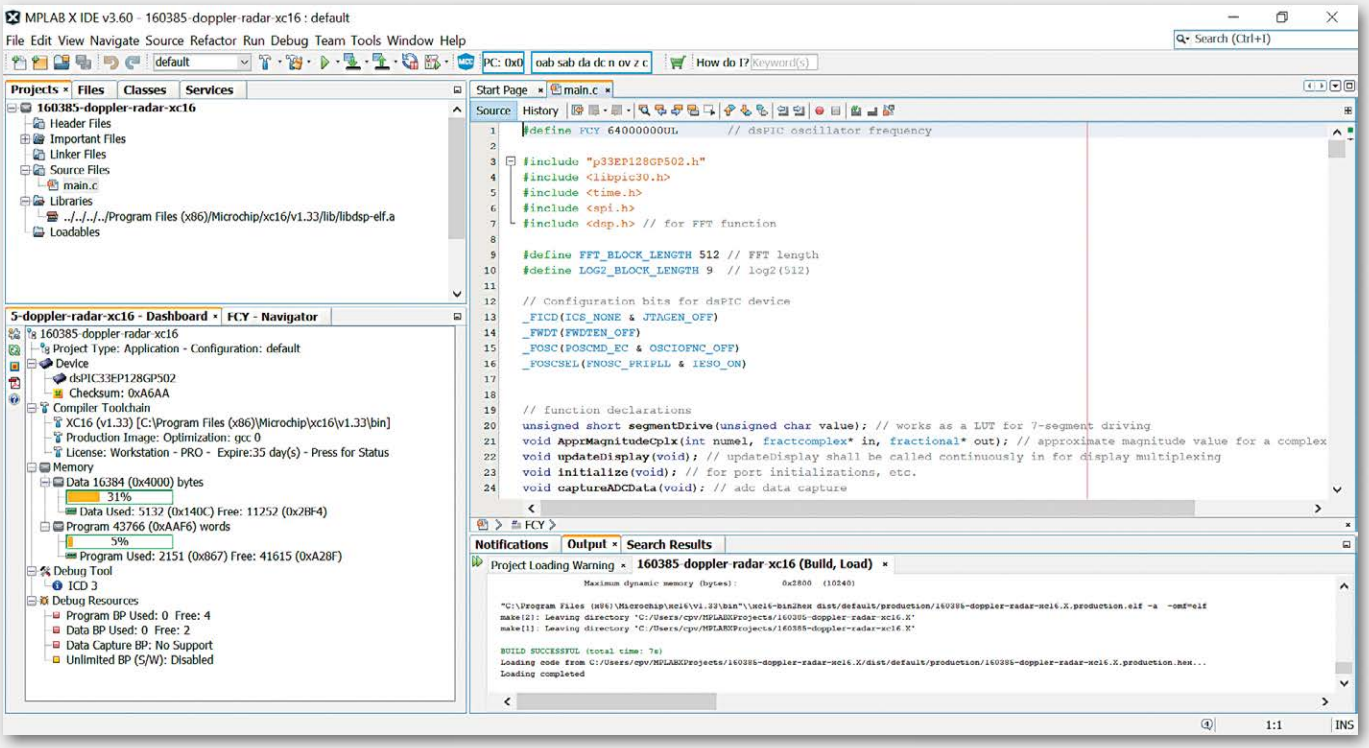
* see text for options and considerations





Compiling the software

To compile the software for this project you will need Microchip's MPLAB X IDE (we used version v3.60) together with a suitable compiler. The actual compiler of choice is XC16 (v1.33 at the time of writing) which supports the dsPIC family. Although officially you need a licence to unleash all its power, it works fine without one. XC16 includes the library libdsp (we used libdsp-elf.a) required for this project. You can download the project from [1]. Those who want to set up their own project only need the file main.c and the libdsp library. Compile for the device dsPIC33EP128GP502.



of the controller's I/O ports, timer and interruption operation, as well as initialisation of the Fast Fourier Transform (FFT) library. When done the processor enters the main loop.

Every iteration starts by switching on the radar transceiver and waiting for a while to allow the module to get ready for operation. Then 512 samples are taken from the input signal and get stored into an array of 16-bit integer values. As soon as the data has been captured it can be processed. While this is happening the radar module is switched off in order to conserve battery power.

Oh my giddy aunt, an FFT!

Signal processing includes a windowed FFT. Microchip provides a DSP library with the Microchip C30 Toolsuite for dsPICs (see inset) containing all the functions to do this. Using this library, first a Hanning window is applied to the data to correct it for the fact that the data length is not infinite. Then the FFT is calculated and the output is rearranged (bit-reversed) to get it into a practicable order. Because the input of the FFT are real values (as opposed to complex), only the first half of the output array — i.e. elements 0–255 — contains useful data while the other half is redundant. Each element of the array — i.e. each bin — corresponds to a frequency equal to $i \times F_s / 512$, where i is the element's index or *bin number* and F_s the sampling frequency (60/3 kHz; as 3 samples are averaged into 1). The frequency difference between two bins of the FFT output is about 39 Hz (20 kHz / 512). According to the Doppler-shift formula above this corresponds to a speed of about 0.24 m/s and this determines the resolution of our Doppler radar.

A little light trickery

The FFT output is an array of fractional complex numbers. The signal amplitude or magnitude, which is what we are interested in here, can be calculated by taking the square root from the sum of the squared real (a) and imaginary (b) parts:

$$\text{Magnitude} = \sqrt{(a^2 + b^2)}$$

The computationally costly square root calculation can be avoided by using an approximation. Several methods for calculating the approximate magnitude of a complex number exist; I used the equiripple-error approximation method presented in reference [3]. More details about this approximation can be found in the source code comments [1].

Target detection

At this point the signal amplitude in each frequency bin is known. If the radar beam was reflecting off a target, there will be a signal with a frequency corresponding to the target's speed (towards or away from the radar). This signal can be detected because the magnitude of the corresponding frequency bin exceeds the detection threshold. If there are no

targets, only noise is present and the bin magnitudes are all below the detection threshold. In this project a fixed, experimentally determined detection threshold is used that avoids false detections as much as possible.
In the final stage of the signal processing chain the frequency bins are searched to find the highest frequency that exceeds the detection threshold. This corresponds to looking for the highest valid target speed. If found this bin number is stored and kept for about one second in order to have a readable display without flickering. The magnitude is converted into a speed value in km/h with the help of a precomputed look-up table.
Taking one measurement, i.e. sampling the input signal and processing it, takes about 25 ms. After each measurement the processor updates the display and waits for about 100 ms before starting all over. Measurements are therefore taken at a rate of about eight times per second.

Assembly and testing

The circuit board is a double-sided board with dimensions of about 100 × 80 mm. Although this project concerns an experimental Doppler radar care has been taken to apply good design practices to keep the analogue and digital parts well apart.
The 7-segment displays are mounted at the top side together with the battery holder; all other components live at the bottom side of the board. The radar transceiver module can be mounted at both sides, straight or rotated by 90°. The reason for this is that the aperture angle is different for the *x* and *z* axes (azimuth & elevation). To facilitate experimenting with the module's orientation we have provided K5 to K8.
Most of the components are pretty small surface mount assembly (SMA) parts. The dsPIC's package for instance is a 28-pin SSOP with a 0.65-mm pitch and it can be somewhat challenging to solder by hand. However, with a good soldering iron, a modest microscope and/or good glasses and some practice even the smallest components used in this circuit can be soldered by hand. The only device that's really hard to mount (in our opinion), IC4, can be avoided by taking the IC11 road (see above).
The circuit board is mounted in a standard, sturdy polycarbonate enclosure (NEMA 4X, i.e. watertight and suitable for outdoor use) with a transparent cover.

Web Links

[1] Free downloads for this article: www.elektormagazine.com/160385
[2] Gregory L. Charvat: The Future of Small Radar Technology, *Circuit Cellar*, April 2014.
[3] Richard G. Lyons (ed.), Streamlining Digital Signal Processing, *IEEE Press*, 2007.

The display is clearly visible through the cover while the electronics are more or less protected from impacts like balls, for example.
The radar was tested during floorball training sessions (floorball is a kind of hockey with a ball) and it turned out to be capable of detecting a 7 cm-diameter plastic ball at a distance of several metres. A car can be detected at a distance of about 50 to 100 metres (60 m according to the radar module's specifications). I did not perform any thorough validation of the speed measurement's accuracy but at least the car speed measurements were in line with speeds given by my car's speedometer.

Final thoughts

I am quite happy with the results of this project. The Doppler radar is at least a nice toy and has potential in many other applications as well. The project turned out to be very educational as well as it was the first time I used a digital signal controller. In previous projects I have used 8-bit microcontrollers or bigger processors like the ones typically found on Raspberry Pi and BeagleBone boards. It took some time to get the Fourier transform, which is the signal processing core in this application, up and running. Examples and documentation provided by Microchip have been of great help here. The digital signal controller turned out to be reasonably efficient in this kind of signal processing work and it is an interesting addition to my toolbox for future projects.
If the radar transceiver module raised your interest, it is not necessary to build a circuit board right away. I started experimenting with the module simply by connecting the IF outputs to the soundcard of my PC. On the PC I used SDR software which accepts the sound card signal as an input and has nice spectrum and spectrogram displays for inspecting the frequency content of the signal. With this kind of simple setup it is possible to get a good idea of the radar module operation and the kind of targets detectable with it.

Other applications

Because the radar module contains all the specialised circuitry, the mainboard is actually a quite universal DSP board with a 16-bit, 100-kSps ADC and a large 3-digit 7-segment display. Connector K5 (or one of its brethren) provides a convenient input with a switchable 5-volt power supply to mate with an extension input board of your own devising. Parts R42 and K2 offer even more flexibility when buffer opamp IC10 cannot be used. Connectors K3 and K4 allow for controlling other devices or to communicate with them. Housed in its sturdy watertight enclosure all sorts of applications can be imagined and realised with this design. ⏮

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→ Experimental Doppler Radar, bare PCB
www.elektor.com/doppler-radar-pcb

→ dsPIC33EP128GP502, programmed
www.elektor.com/doppler-radar-dspic

→ K-LC5 Doppler radar transceiver
www.elektor.com/k-lc5